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A novel steam ejector with auxiliary entrainment for energy conservation and performance optimization

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ABSTRACT

In this study, it is found that there exist several low-pressure regions whose pressure is lower than that of the entrained steam inside the ejector under both its designed and non-designed conditions. Thus a novel steam ejector with auxiliary entrainment is proposed to take full use of the possible low-pressure regions to entrain the extra low-grade entrained steam for energy conservation and performance improvement. The internal flow fields in the steam ejector with and without auxiliary entrainment have been obtained numerically. Analysis and research are mainly focused on the influences of the mixing chamber, ejector throat, diffuser auxiliary and combined auxiliary entrainment on the mass flow rate, the entrainment ratio, the internal pressure field and the shock wave phenomena of a given ejector. The results reveal that the throat and diffuser auxiliary entrainment can increase the entrainment ratio of the steam ejector under the simulated operation conditions. The throat auxiliary entrainment is a feasible choice for ejectors operating under the designed conditions and the combined auxiliary entrainment of the throat and the diffuser is the best choice for ejectors operating under non-designed conditions.

1. Introduction

As the basic guarantee for human survival and social progress, energy source is a bottleneck for sustainable development of any country. However, excessive consumption and unreasonable waste of energy for meeting the rapid economic development has caused serious energy shortage and environment pollution problems. On the other hand, a huge amount of low-grade energy is being wasted directly without reasonable management or conversion applications in various industrial processes. Thus energy conservation is of crucial importance for the sustainable development of both economy and society. Steam ejector is a type of economically-feasible fluid machinery which can entrain low-pressure steam (entrained steam) by consuming a certain amount of high-pressure primary steam. So, in this sense, it is a kind of compressor that promotes the fluid pressure and thus improves the quality of low-grade heat energy of the entrained steam without consuming mechanical work [1]. And this low-grade energy is available in various industrial processes. In some situations, the application of ejectors helps to recovery a large part of the waste heat of the entrained steam and thus produce energy saving. Therefore, steam ejectors have been finding more and more applications in various industrial processes. For example, the multi-effect distillation systems of seawater desalination with steam ejector have a higher performance ratio for the effective utilization of low pressure vapor energy [2]; The vapor-compression refrigeration cycle with supercooling using an ejector can increase the cooling capacity and coefficient of performance (COP) compared to the single-stage vapor compression refrigeration cycle [3]; The proton exchange membrane fuel cell (PEMFC) system equipped with ejector can realize hydrogen recirculation with low enough flow resistance [4], and a well-designed ejector can significantly increase the ejector recirculation ratio for achieving high efficiency of PEMFC system [5].

As important as it can be, the structural design method is far from satisfactory. Actually, the entrainment ratio of the designed steam ejectors is usually far smaller than its theoretical value, only 20–50% of that, if not anything smaller. This of course causes the poor performance and limits its wider and more efficient application. Therefore, how to improve the ejector performance for energy conservation has become a hot topic and received more attentions from both industries and scientific researches nowadays. Many scholars have analyzed comprehensively the influences of working and structural parameters on the steam ejector performance. The internal flow field and shock wave phenomena have being studied using the numerical simulation and experimental methods. The

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Nomenclature

p_P	primary steam pressure, kPa
p_H	entrained steam pressure, kPa
p_C	mixed steam outlet pressure/back pressure, kPa
Δp_w	near-wall pressure variation, kPa
Δm_P	primary steam mass flow rate increment, g/s
Δm_H	entrained steam mass flow rate increment, g/s
ε_μ	entrainment upgrade ratio, %
Δm_{h1}	auxiliary entrained steam mass flow rate increment of the mixing chamber, g/s
Δm_{h2}	auxiliary entrained steam mass flow rate increment of the ejector throat, g/s
Δm_{h3}	auxiliary entrained steam mass flow rate increment of the diffuser, g/s
β	compression ratio
μ	entrainment ratio
COP	coefficient of performance
PEMFC	proton exchange membrane fuel cell
NXP	nozzle exit position
BOG	boil-off gas
EVIC	enhanced vapor injection cycle

experimental results of Huang et al. [6] and the numerical results of Wang et al. [7] both proved that there does exist a critical value for the mixed steam outlet pressure of ejector under given primary and entrained steam pressure conditions. Exceeding this critical pressure will break the double choking state and result in the fast degeneration of the ejector performance. Chen et al. [8] developed a new one-dimensional model that can be used to predict ejector performance over a wide range of operation parameters. Their work is a good reference for designing steam ejector structural parameters. Besides the work parameters, more work has been aimed at optimization of structural parameters. The numerical study of Wu, et al. [9] proved that there is an optimum range of the mixing chamber length for steam ejectors obtaining its best performance, and the mixing chamber convergence angle also has an optimum value at which the steam ejector acquires its largest entrainment ratio. These conclusions are in good agreement with Ji [10] and Zhu [11]. There are also numerous studies on the structural parameters of the primary nozzle due to their crucial effects on the ejectors performance. Pianthong et al. [12] investigated the performance of an ejector with NXP (the primary nozzle exit position) varying from −15 mm to 10 mm, and their numerical results showed that the entrainment ratio increased slightly as NXP was moved further from the inlet section. However, Chen [13] revealed there is always an optimum NXP that makes the ejector have the best performance, which decreases with primary steam pressure. Fu et al. [14] further optimized the outlet diameter and the divergent section length of the main nozzle numerically, and it was disclosed that the outlet diameter has a critical value at which the ejector acquires its best performance and there is only a weak effect on the ejector performance for the divergent section length. Many efforts have also been made to improve the steam ejector performance by changing its structure. Xing et al. [15] used the double ejector system to improve the performance of the two-stage trans-critical CO_2 heat pump cycle. Their simulation results showed that the COP and volumetric heating capacity can be boosted by 10.4% and 6.3%, respectively. Tan et al. [16] also proposed to use double ejector system and proved that this system can reduce the energy loss and suck an amount of fuel BOG (boil-off gas) into the compression system. A lobes circular nozzle and a petal nozzle were deployed by Opgenorth [17] and Chang [18] to enhance the ejector performance. Comparing with conventional conical nozzle, these nozzles do have larger area ratio of constant area section to nozzle throat and a better performance. Wang et al. [19] proposed a novel ejector with an additional flash tank for the enhanced vapor injection cycle and the EVIC (enhanced vapor injection cycle) have about 3% improvement in coefficient of performance.

Generally speaking, the studies mentioned above trying to improve the steam ejector performance by changing the relative geometric shape or the size of each part are based on conventional steam ejectors, that is, the basic structure remained unchanged. Therefore, these renewed ejectors basically consist of the fixed nozzle, the suction chamber, the mixing chamber and the diffuser. Obviously, this kind of fixed-structure ejector can achieve the best working performance only under the designed working conditions, and the optimization scheme can be obtained only under specific working parameters or structural parameters. However, operating conditions may change, such as the changes of external steam work parameters, especially the primary steam pressure fluctuation for multi-condition operation processes. The departure from the designed working conditions will inevitably result in the steam ejector performance deterioration. This is because the optimum design geometries of a specific steam ejector are determined according to a given pressures of the primary steam. If the primary steam pressure is too high, there will be superfluous pressure and velocity; if the pressure is too low, there will be insufficient entrainment flow and even reflux. To make full use of this superfluous energy of the superfluous pressure and velocity, Chen et al. [20] proposed a novel ejector with a bypass to enhance their ejector performance for various operational parameters. Their results showed that the proposed ejector does have relatively high entrainment ratio. It should be pointed out that Chen et al. found only one low-pressure area where exists superfluous energy around the second shock position of the diffuser. However, in fact, as the numerical simulations of this paper will show that there are many low-pressure areas inside the injector, not only in the diffuser, but also in mixing chamber and throat regions.

In this paper, a detailed numerical simulation is made of a steam ejector and the results disclose that there still exist some low-pressure regions where the fluid pressure is significantly lower than that of the entrained steam inside the ejector both under the designed and non-designed operation conditions. And this pressure difference actually can be further used. Based on this finding, a novel steam ejector with auxiliary entrainment is proposed to take full use of the pressure difference between all low-pressure regions and the entrained steam to entrain the additional entrained steam into the steam ejector and thus increase the entrainment ratio which is a main indicator of steam ejector performance. Its effectiveness is verified by the following detailed numerical simulation of internal flow field, shock wave under various conditions. Based on the analysis of systematic numerical results, the optimum auxiliary entrainment scheme is given for different working parameters in this paper.

2. Structure and CFD model of steam ejector

The auxiliary entrainment type steam ejector is mainly composed of the following five parts: the primary nozzle, the suction